

A Study Of An optical Lunar Surface Communications Network With High Bandwidth Direct To Earth Link

K. Wilson, A. Biswas and J. Schoolcraft
Communications Tracking and Radar Section
Jet Propulsion Laboratory California Institute of Technology
Pasadena CA, USA

Abstract— A lunar surface systems study explores the application of optical communications to support a high bandwidth data link from a lunar relay satellite and from fixed lunar assets. The results show that existing 1-m ground stations could provide more than 99% coverage of the lunar terminal at 100Mb/s data rates from a lunar relay satellite and in excess of 200Mb/s from a fixed terminal on the lunar surface. We have looked at the effects of the lunar regolith and its removal on optical samples. Our results indicate that under repeated dust removal episodes sapphire rather than fused silica would be a more durable material for optical surfaces. Disruption tolerant network protocols can minimize the data loss due to link dropouts. We report on the preliminary results of the DTN protocol implemented over the optical carrier.

Keywords—Lunar optical communications; Disruption tolerant network; Lunar surface systems

I. INTRODUCTION

The International Space Exploration Coordination Group (ISECG) recently reported in its Global Point of Departure (GPoD) on a reference architecture that has identified optical communications as a means of satisfying high-rate communication service to or from Earth. The communication and navigation architecture provides for information exchange between the elements of the lunar exploration. These elements are distributed on the lunar surface, in lunar orbit, and at Earth. Initially the Earth elements will be on the ground but are expected to evolve to Earth-orbiters over time.

Of the variety of communication service classes identified, namely, low-rate communication service; moderate rate communication service; high-rate communication service and emergency communication service, high-rate communication service is defined to cover the data rate range of 10-100 Mb/s. Figure 1 depicts the communication and navigation concept for lunar exploration. The elements and high-rate communication frequencies are all Ka-band links. Some of the elements involved in high-rate communications shown here include: (i) the Earth based ground receive/transmit stations (not explicitly shown in figure); (ii) the Lunar Relay Satellite (LRS) orbiting the Moon and intended to provide coverage of the polar regions of the Moon

when direct with Earth (DWE) communication is obstructed (iii) the Portable Communications Terminal (PCT) that interconnects surface elements and supports links to Earth and/or orbiting relay satellites. Four levels of element communication systems (ECS) are called out in the reference architecture, but only one, the ECS-1, supports high-rate communications.

In Figure 1, the communication zones are demarcated by different colors. The center cream color identifies a region 6 km in radius and corresponds to the service range of the PCT. Assets within this range will communicate directly with the PCT which will relay messages and data to the intended destination. The middle 30 km radius blue zone is the high-rate LRS coverage area, and assets outside the cream-colored zone but within the blue zone will be able communicate directly with the LRS at high-rates. The outer 250 km radius green zone corresponds to LRS coverage with low-rate service only.

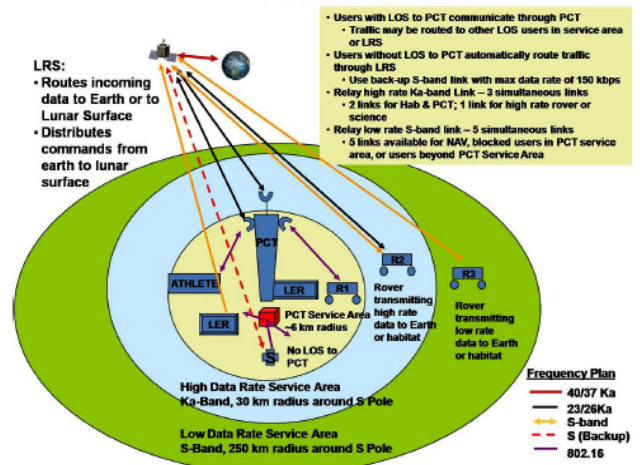


Figure 1. Lunar communication zones and links as defined in the GPoD study.

Data rates called out for the different elements are summarized in Table 1 below. Details of the spectrum

allocation and communications system to support these rates are defined in the Reference Architecture report. It should be noted that the baseline high data rate communications links are achieved using Ka-band.

Table 1: Summary of GPoD data rates for high-rate communication

Element Name	Communicating To	Return (Mb/s)	Forward (Mb/s)
Earth Based Ground Station	LRS or Lunar Surface	100	25
Lunar Relay Satellite	Earth Based Ground Stations	100	25
	Lunar Surface	100	25
Portable (PCT) Communications Tower	LRS	25	100
	Earth based Ground Stations	25	100
	Intra-surface Elements	43	43
ECS - 1	To Earth or LRS	25	6

In this paper we present the results of a preliminary study that addresses the scope for optical communications to service selected functions of the communication and navigation requirements described in the reference architecture with the emphasis on high rate communications. We also identify other communication and navigation services where optical technology could bring to bear some unique capabilities. In addition, we report on the top five challenges to the deployment of optical communications systems on the lunar surface and present preliminary experimental results to address two of these; the disruption tolerant network (DTN) protocol, and lunar dust removal.

The investigation of the optical-to-network layer interface challenge explored the performance of DTN protocols in a built-to-purpose optical link testbed. The testbed was designed to instantiate an operational concept using JPL's DTN protocol implementation in point-to-point topology between a ground station and a space asset. This configuration included a high-rate optical downlink, and low-rate radio frequency return link. Preliminary tests of system performance confirmed the feasibility of optical DTNs and further characterized behavior of JPL's space-purposed implementation of the DTN protocol. Results also highlighted probable avenues for optimization of DTN protocols in optical systems.

II. LUNAR OPTICAL COMMUNICATIONS

A. Case for Optical Communications

Optical communications is an emerging technology. The 1992 GOPEX experiment that with the Galileo spacecraft in deep space highlighted the need to mitigate two key issues in space-to-ground bidirectional optical communications, i.e., the need to address uplink scintillation and for site diversity.^[2] Since GOPEX, multi-beam uplink strategies are accepted in the baseline of ground to space optical links, and the demonstrations listed below have addressed key challenges for a variety of optical links:

- Bi-directional Space-to-Earth links from Low-Earth-Orbit (LEO) and Geo-stationary Orbit (GEO)^[3,4]

Identify applicable sponsor/s here. (*sponsors*)

- LEO to GEO satellites^[5]
- LEO-to-LEO satellites^[6]

Optical communication's key advantage, the capability to transfer high data rates, has the additional benefit of lower mass, power and volume burden on the spacecraft compared to Ka-band radio frequency (RF) systems. It is with this advantage in mind that the ISECG Reference Architecture mentions the possible use of optical communications for LRS-to-Earth high-rate communications. Relevant to this goal, NASA plans to demonstrate bi-directional optical communication between the Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft orbiting the Moon and Earth-based ground stations in 2013. The uplink data rate is 20 Mb/s with downlink rates ranging from 39-622 Mb/s.^[7] The space terminal used for this demonstration would be a forerunner of eventually deployed operational systems that can service the LRS to Earth link.

Although not specifically indicated in the reference architecture, the surface-to-LRS and possible direct-with-Earth (DWE) links can be serviced by optical communications. High-rate lunar surface to LRS links as currently conceived all operate at Ka-band frequencies. However, they are required to be within the middle light blue zone in Figure 1. Optical "proximity" or "access" links can augment this capability by expanding the coverage of high-rate links between surface assets and the LRS, as well as DWE links. Technology development followed by risk retiring demonstrations will be required to implement this capability.

The International Laser Ranging Stations (ILRS) have demonstrated centimeter-level ranging to retro-reflecting satellites and to the lunar retro-reflectors.^[8] While accurate, this approach requires high peak power transmitters and photon counting detectors assets that to compensate for the R^{-4} propagation loss. An alternative approach that is complementary with an optical communications modulation format is a pseudo-random noise (PN) bit stream overlaying the optical data stream that is regenerated and returned to the transceiver. The PN approach is being implemented at radio frequencies within the 70- m, the 34-m High Efficiency (HEF), and the 34-m Beam Waveguide (BWG) subnets.^[9] Recent optical ranging experiments to aircraft have shown that the PN approach is capable of centimeter-level accuracy.^[10]

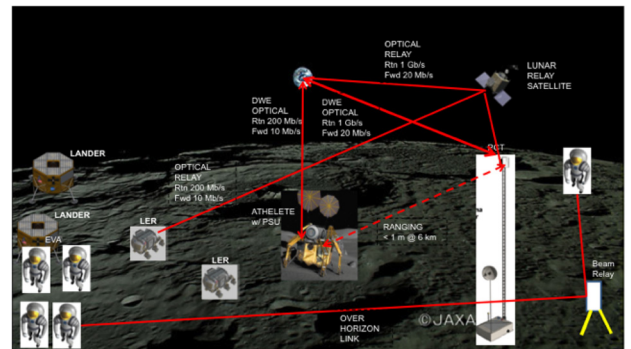


Figure 2. Pictorial representation of direct to Earth and relay links between lunar surface assets, PCT is in the foreground.

A. Optical Links in the Lunar Network

Communications to and from lunar surface assets will be supported either by direct links or by relay links when direct line-of-sight (LOS) between Earth-based ground stations and the lunar surface cannot be maintained. Figure 2 is a pictorial representation of the optical links shown by the solid red lines. The orbital characteristics for the LRS are based on a JPL Team-X Design Study that identified stable lunar orbits, with minimal station keeping to support maximum polar coverage.^[11]

B. Link Analysis

The baseline optical link approach is a 1550-nm downlink from the moon, either surface asset or LRS with a 1030-nm uplink from the Earth stations. A point design link summary is shown in Table 2; the baseline position in the analysis was to retain a 3dB margin on the link. On the uplink, multi-beam strategies used to mitigate scintillation fades caused by atmospheric turbulence require eight 5W beams 10-cm in diameter for a total output power of 40W. The point design calls for an 80 μ rad uplink beam divergence to compensate for a conservative estimate of 10 μ rad pointing bias and 13 μ rad jitter at the transmitter. The uplink modulation format modeled is binary-PPM (pulse position modulation) similar to what JPL used in the 1995 ETS-VI and 2009 OICETS optical communications demonstrations.^[3,4]

Table 2: Moon-Earth optical link summary, point design; 1-m Earth receiver.

Description	Lunar Tx, W	Lunar Tx/Rx dia, cm	Data rate Mb/s	Wavelength, nm	Comments
Return Lunar mobile to Earth	1	5	>200	1550	
Return Lunar stationary to Earth	1	10	>1000	1550	
Forward Earth to Lunar mobile		5	>1	1550 (1030)	40-W total power in 8 beams in 80 μ rad (1/e ²) beam.
Forward Earth to Lunar stationary		10	>10	1550 (1030)	

On the return link from the moon the 1-m class Earth-based optical antenna not only provides a large antenna gain to support a high bandwidth [0.2Gb/s to >1Gb/s] link from a small [5cm to 10 cm] low power [1W] lunar transmitter, but also mitigates atmosphere-induced signal fading by aperture-averaging the fluctuations of the signal across the 1-m aperture. The link assumes an OOK (on-off-keying) downlink modulation format.

In the next three sections we discuss the Earth-LRS and LRS-Lunar asset links in detail and consider operations scenarios for the high rate optical downlink.

C. Earth to LRS Link

Taking advantage of the international partnering articulated in the reference architecture description, a ground network configuration comprised of three existing optical ground stations was considered. The stations were: (i) NASA's 1-meter OCTL (Optical Communication Telescope

Laboratory) telescope located at Table Mountain, CA in the United States;^[12] (ii) The 1.5 m Optical Ground Station (OGS) in Koganei, Japan^[13]; and (iii) ESA's 1-m Optical Ground Station in Tenerife, Spain.^[14]

The plot of the elevation angles of the LRS from these three locations in Figure 3 shows that these ground stations provide complete coverage of the LRS with some overlap, i.e., simultaneous visibility from 2 stations. Figure 3(a) shows the moon's elevation from these stations over a thirty-day period. Figure 3(b) is a section of Figure 3(a) with the time axis expanded for better resolution.

The near continuous coverage depicted in Figure 3 will be reduced by the presence of clouds. In principle, the loss of link availability due to cloud cover can be restored by site diversity. The number of ground stations is expanded to form a ground network with stations located in uncorrelated weather cells. This strategy will require substantial investment at the very start. However, if the optical links are assigned the function of "bursting" down huge volumes with link availability constraints due to clouds and weather, they can still contribute to a substantial improvement in service. The storage capability on the LRS also can largely mitigate weather outages.

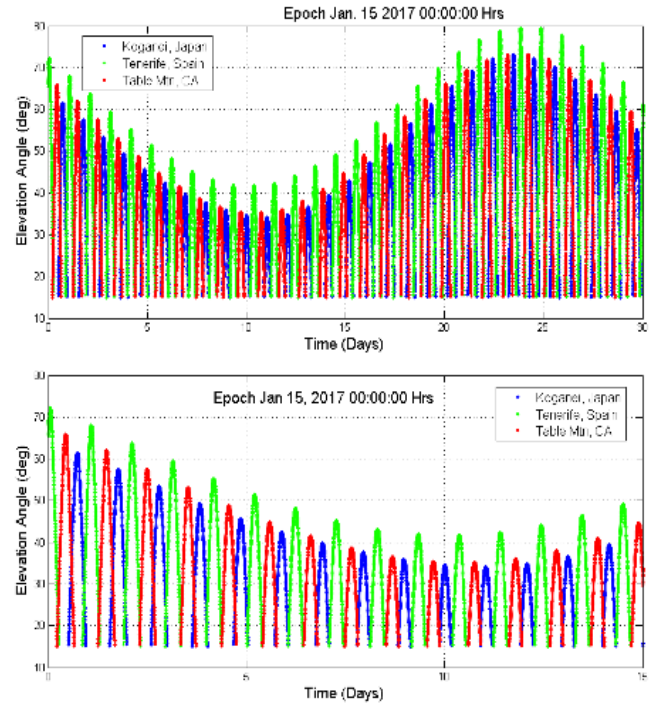


Figure 3. (a) Upper figure shows elevation angles of the moon as viewed from Earth stations over thirty-day period. (b) Lower figure is an expanded scale that shows complete coverage over the duration.

As an example, cloud-free line-of-sight studies using satellite data indicate an average availability of 60% at Table Mountain, CA, 40% at Tenerife, Spain and 25% at Koganei, Japan. Using data rates (0.62 Gb/s) of the 2013 NASA Lunar Laser Communication Demonstration (LLCD), 2,799 GB per day will be received from the Moon with the three-station ground network and its assumed availability. Currently, the Lunar Reconnaissance Orbiter (LRO) returns 461 GB of data per day.^[15] It is reasonable to expect at least factors of 2 to 4 data rate increase for optical links if they are implemented in the 2016 time frame. Furthermore, better ground station locations such as Hawaii (65% availability) can be utilized instead of Koganei, Japan. This can provide almost an additional order of magnitude increase in the average data volume return (14,493 GB per day). Overlap periods on the order of an hour when the link can be accessed from either of Table Mountain or Koganei and Tenerife or Koganei also mitigate the effects of adverse weather at the ground stations.

D. LRS-Lunar Surface Link

The LRS-to-lunar surface asset optical link is based a lander located on the Malapert Peak in the South Pole region (89° latitude, 0° longitude and 5-km altitude) of the Moon.^[1] Furthermore, analysis presented here presumes a single orbiting LRS. Figure 4a shows a 5-day and Figure 4b a 30-day plot of the elevation angles for viewing the LRS from the fixed lunar surface location. The variation of range for the surface to LRS links is shown in Figure 5.

Operating the lunar surface to LRS link will require optical transceivers be deployed on the lunar surface assets. Optical transceivers deployed on the surface assets will be capable of autonomously acquiring and closing the optical link with the LRS. To this end, these assets will be equipped with an all-sky camera to view the LRS downlink initiated by the LRS. The gimbaled transceiver will acquire and lock on the LRS laser beam and uplink a beacon. This will be followed by an initial handshake and subsequent data exchange. A proof-of-concept for this scenario was successfully demonstrated using an overflying aircraft and a ground-based transceiver at JPL where uncompressed video imagery at 270 Mb/s was streamed from the ground to the aircraft over slant ranges of 5-9 km.^[16,17,18]

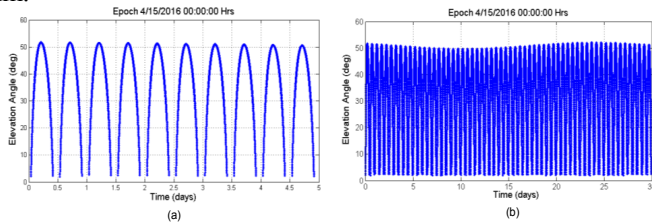


Figure 4. Five day and thirty day plots showing LRS optical link availability to asset at the South Polar lunar region.

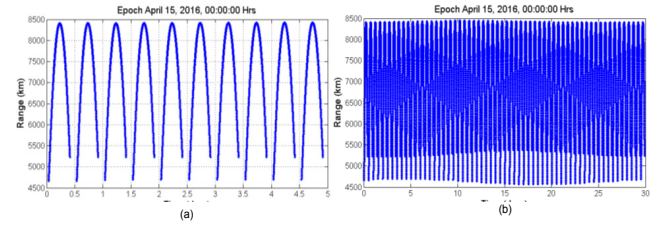


Figure 5. Variation in range between asset at southern region and LRS over thirty-day cycle

E. Operational Scenarios

Two scenarios can be envisioned for transferring data from the lunar surface to Earth on the optical link. The first is a store-and-forward process where data returned from the surface to the LRS is buffered for subsequent re-transmission to Earth. In this store-and-forward scenario a single optical transceiver on the LRS can service the surface assets and the Earth-based ground receivers. The required buffer capacity on the LRS is expected to be less than 1-terabyte (100Mb/s for 24 hours) and would be determined by availability based on coverage and joint weather statistics of the ground stations.

A second approach would be direct-to-Earth streaming of imagery from high-definition cameras on board lunar landers or rovers. This capability will be especially useful for transferring imagery back to Earth from the regions being explored that are not covered by the high-rate Ka-band service, and a 10-cm lunar-based transmitter with modest output power could support a link in excess of 1Gb/s to a 1-m ground station.

III. CHALLENGES TO DEPLOYING LUNAR OPTICAL COMMUNICATIONS

In a series of Lunar Surface System meetings and communiqués with JSC, GRC, ITT, LARC, GSFC and other JPL personnel we identified the top five risks to the deployment of optical communications on a lunar mission, namely:

1. Effects of blast ejecta (lunar dust) on optical surfaces
2. Transparent interface of optical physical layer to network and higher Lunar comm/nav layers
3. Acquisition and tracking without impeding mobility of mobile assets
4. Thermal cycling through lunar diurnal cycle and survivability of optical components and lasers
5. Long-term life cycle effects such as laser/detector lifetimes in lunar environment

We chose to investigate two of these risks: the effects of lunar dust, and a protocol on a free space optical link that would provide a transparent interface to higher communications layers while supporting disruptions due to intermittent obscuration in the line of sight. Acquisition and tracking of mobile assets, thermal cycling, and long-term life cycle effects required a time commitment that exceeded what was available for this task. The team envisioned the Desert RATS program as a possible opportunity to investigate

acquisition and tracking scenarios of mobile assets and a field demonstration of the disruption tolerant network (DTN) protocol over optical carrier.

A. Lunar Dust Removal

The major constituents of the lunar regolith are silica and alumina; constituents that have Moh's hardness comparable to and greater than glass, respectively.^[19,20] Optical components such as lenses and optical flat surfaces in the transceiver optical train that are exposed to the lunar dust and left unattended will, over time, degrade in optical transmission to a degree that would preclude closing the link. Methods to remove the accumulated lunar dust from these optical surfaces include the deposition of carbon nanotube and Indium Tin Oxide (ITO) electrodes.^[21,22]

We have looked at the removal of 50–75 μ m JSC-1A lunar dust simulant by indium tin oxide (ITO) electrodes deposited on transparent optical surfaces. A 3-phase spiral electrode pattern was etched on one surface of each sample. The BK7 sample was wired for dust removal tests; the harder fused silica sample was kept as a control to evaluate the effect of the deposition on the wavefront quality of the substrate. Figure 6 shows the spiral 150nm–200nm thick ITO electrode pattern deposited on a fused silica substrate at Kennedy Space Center (KSC).

The transmission wavefront error was measured using a Zygo interferometer. Pre and post deposition interferograms of the substrates show that the sample is essentially flat; with 0.04 waves slope across the surface and 0.13 waves peak-to-valley roughness across the sample. The post deposition interferogram shows no distortion in the sample's surface quality and an electrode deposition height of 0.31 waves [\sim 150nm–210nm] in the visible.

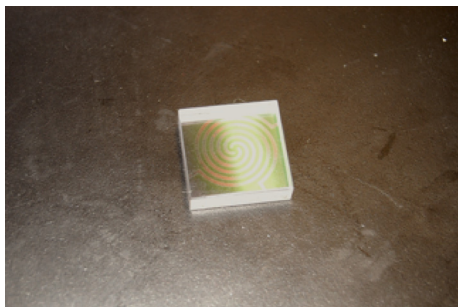


Figure 6. Electrode pattern deposited on fused silica substrate

Figures 7a, 7b and 7c show the sample in the vacuum chamber with dust dispersant equipment prior to dust dispersal, after dust dispersal, and after dust removal with application of electric field. The figures show that in both cases the vast majority of the simulant was removed in the area of the electrodes when the voltage was applied.

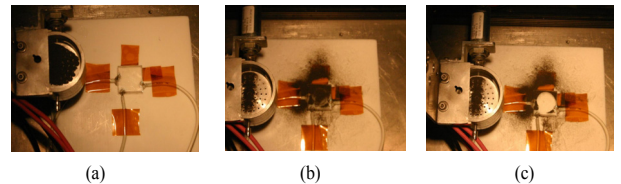


Figure 7. (a) Sample in vacuum chamber prior to deposition of 50–70 μ m JSC-1A lunar dust simulant (b) dust deposited on sample, (c) 3-phase field applied and dust removed.

Evaluation of the samples after dust removal showed that the electrode pattern (i) introduces a phase change in a beam transmitted across the full aperture that would introduce aberrations in the far-field pattern; (ii) scattering from the electrodes would reduce the transmission through the substrate; (iii) the abrasive regolith left scratch marks on the glass after its removal; see figure 8. This would suggest the use of the harder sapphire windows and optics for lunar surface assets.

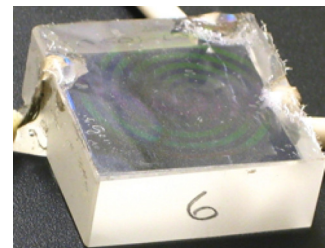


Figure 8. BK-7 glass sample after lunar simulant dust was removed showed surface scratches limiting the useful life of silica windows.

B. Disruption Tolerant Network

The application of the disruption tolerant network (DTN) protocol to a solar system internet and experiments on the Deep Impact spacecraft have been described in the open literature.^[23,24] This work has informed us on an approach to apply this technology to the optical communications link; a link that can be subject to random outages caused by cloud cover and other obscuring factors. Preliminary laboratory testing of the DTN protocol was conducted over an optical link with systems assembled in point-to-point topology. The DTN protocol software used was JPL's Interplanetary Overlay Network (ION), and the optical link was created using two Perle media converter systems.^[25] A schematic of the configuration in Figure 9 shows a high-rate free-space optical link with a backchannel copper Ethernet link. This asymmetric data rate configuration was chosen to mimic operating concepts of a unidirectional optical communications scenario.

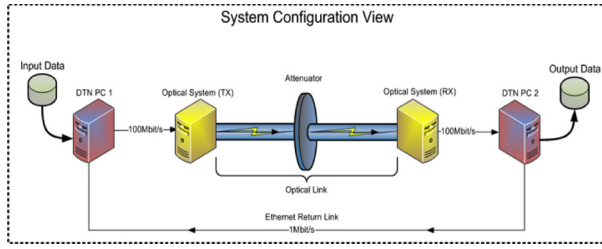


Figure 9. System diagram of DTN protocol and optical carrier

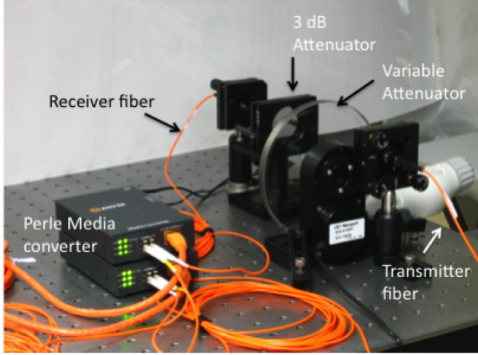


Figure 10. Free space optical path integrated to disruption tolerant network link.

Figure 10 shows the actual optical link hardware as configured for the optical-DTN experiments. The variable attenuator was used to produce forward link outages at nonuniform intervals during testing. Data was sent through the system in a series of DTN protocol units (bundle) with varying sizes. Throughputs reached rates at or above 80Mb/s, and bursted above 100Mb/s. The maximum throughput of the underlying network and optical layers was measured at approximately 800Mb/s. The differential was determined to be caused by software processing delays and protocol implementation details.

While ION is designed to operate in a space environment, the higher-speed portions used for these tests were written with large network performance and congestion management in mind, similar to TCP. Although this is not required to operate a DTN, it can benefit overall system performance when overlaying in larger multi-hop networks (such as the terrestrial internet). In our optical topology, results show the default congestion control mechanism to be very conservative with link resources, especially given that data loss could not be caused by network congestion. This suggests that adjustment or redesign of the congestion mechanism would improve overall throughput performance.

IV. CONCLUSION

We have presented a point design for an optical communications link that could support the high data rate return requirements of a lunar surface network. The results show that with 1W transmitted power from a 5-cm aperture on the lunar surface a data rate of 10Mb/s from the Earth and a 200Mb/s return link to either a lunar relay satellite or to a 1-m class ground telescope can be supported. We have also shown

that existing 1-m class telescopes at Table Mountain CA, Koganei, Japan, and Tenerife, Canary Islands can provide greater than 99% coverage from a South Polar lunar location. It is noted that mitigating the effects of cloud cover to deliver the required link availability would demand additional telescopes to provide site diversity at each of these locations.

We identified the top five technology challenges to the deployment of the technology on the lunar surface and have performed an initial assessment on two of these, namely the lunar dust removal and the disruption tolerant network protocol to mitigate the effects of obstructions temporarily in the transmitter-receiver line of sight. Addressing the other challenges - acquisition and tracking without impeding mobility of mobile assets, thermal cycling through lunar diurnal cycle and survivability of optical components and lasers, and long-term life cycle effects on optical components lifetimes in lunar environment - were beyond the scope of this study.

Our assessment of the KSC dust removal technology to mitigate the effect of the lunar regolith on optical surfaces is that while the approach removes most of the regolith, the electrodes will introduce some loss in transmission and may introduce some wavefront aberration that would result in an increase in the transmitted beam divergence. The results also showed that the abrasive lunar simulant scratched the BK7 sample surface. Based on the composition of the regolith, it is believed that a sapphire optical surface would better withstand the abrasive effects of continued dust removal than would glass or fused silica. Further studies are needed to assess the effects of the degraded beam divergence introduced by the electrodes and to quantify the durability of the substrate under repeated dust removal cycles.

We have performed the first experiments that demonstrate the DTN protocol over an optical link. These initial results are very encouraging and suggest that the architecture could be better optimized to take advantage of optical communications by bursting high rates of data when the link becomes available. Future work in this area is strongly encouraged, and it needs to be coupled with a system design (transmitter, receiver, and laser power) to ensure that the link would support the required increase in data rate to transmit the buffered data corresponding to a representative outage period.

VI. ACKNOWLEDGEMENTS

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